NEOTECTONIC DEFORMATION OF PLEISTOCENE DEPOSITS ALONG THE SUDETIC MARGINAL FAULT, SOUTHWESTERN POLAND

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ABSTRACT

The 160 km long Sudetic Marginal Fault (SMF) of Middle Silesia, southwestern Poland, is a main Alpine fault oriented NW–SE. This paper provides evidence of possible neotectonic activity in front of the SMF. The data are based on three exposures in the Roztoka–Mokrzeszow Graben near the city of Swidnica. Morphotectonic evidence in front of the SMF is also examined. Two sets of extensional deformation features are exposed and analysed. The main one includes gently inclined normal faults and flexures, with displacements in the bedrock of at least several metres. Based on the Quaternary stratigraphy of the region, the age of deformation is most probably Lower Saalian (Upper Pleistocene). The trigger for the deformation was probably the reactivation of the SMF and other faults due to the advance of the Lower Saalian Scandinavian ice-sheet into the Sudetic Mountains. The secondary deformation system includes sub-vertical, often conjugate faults with displacements up to 0·5 m superimposed on former structures. Its dominant normal faulting mode suggests an extensional stress regime that apparently coincides with the post-glacial glacioisostatic rebound. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The Sudetic Marginal Fault (SMF) in Middle Silesia, southwestern Poland (Figure 1), is a 160 km long, probably normal listric fault (Cwojdzinski *et al*., 1995) oriented NW–SE. It is the main Alpine tectonic line bordering the Bohemian massif in the northeast. Although the Sudetic marginal tectonic zone originated in Late Palaeozoic times (Oberc and Dyjor, 1969), the fault was formed in the Late Oligocene–Early Miocene period and reached its maximum vertical separation (up to 1000 m) during the Pliocene (Grocholski, 1977; Dyjor, 1975, 1983, 1986). The SMF comprises a clear and often sharp scarp, bordering the Sudetic Mountains in Poland and the Czech Republic. Neogene grabens, 100–400 m deep (Dyjor and Kuszell, 1977; Dyjor *et al*., 1978; Ciuk and Piwocki, 1979), separate the uplifted Sudetic Mountains from the Sudetic foreland and the Silesian lowlands which form the downfaulted northeastern part of the Bohemian massif.

The regional extensional tectonics on the NE foreland formed a set of steep antithetic faults and grabens close to the SMF (Figures 1 and 2), and uplifted blocks at greater distances. Extensive basaltic volcanism, especially on uplifted blocks (Figure 1), was active between the late Oligocene and early Pliocene, although some basaltic necks indicate Lower to Middle Pleistocene age (Birkenmajer *et al*., 1970; Sibrava and Havlicek, 1980). This suggests that although extension on the NE foreland of the Sudetic Mountains reached its peak during Miocene–Pliocene time, it continued to Middle Pleistocene. The increasing thickness of the Quaternary deposits in the grabens (Dyjor and Kuszell, 1977; Dyjor *et al*., 1978; Kural, 1979; Ciuk and Piwocki, 1979) suggests active subsidence at that period.

It has been proposed that the SMF was inactive during the Quaternary period (Dumanowski, 1961; Oberc and Dyjor, 1969). However, Zeuner (1928) suggested Middle/Upper Pleistocene tectonic uplift of the Sowie

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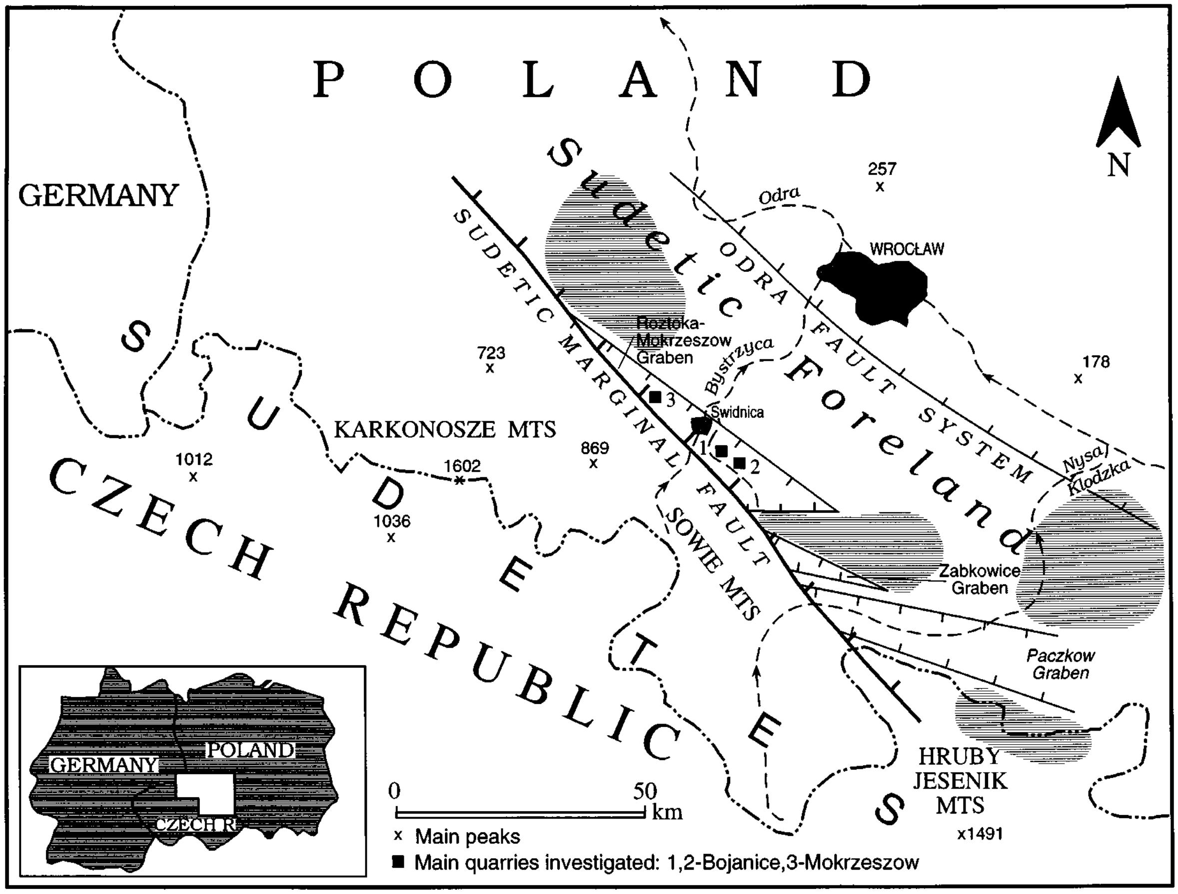


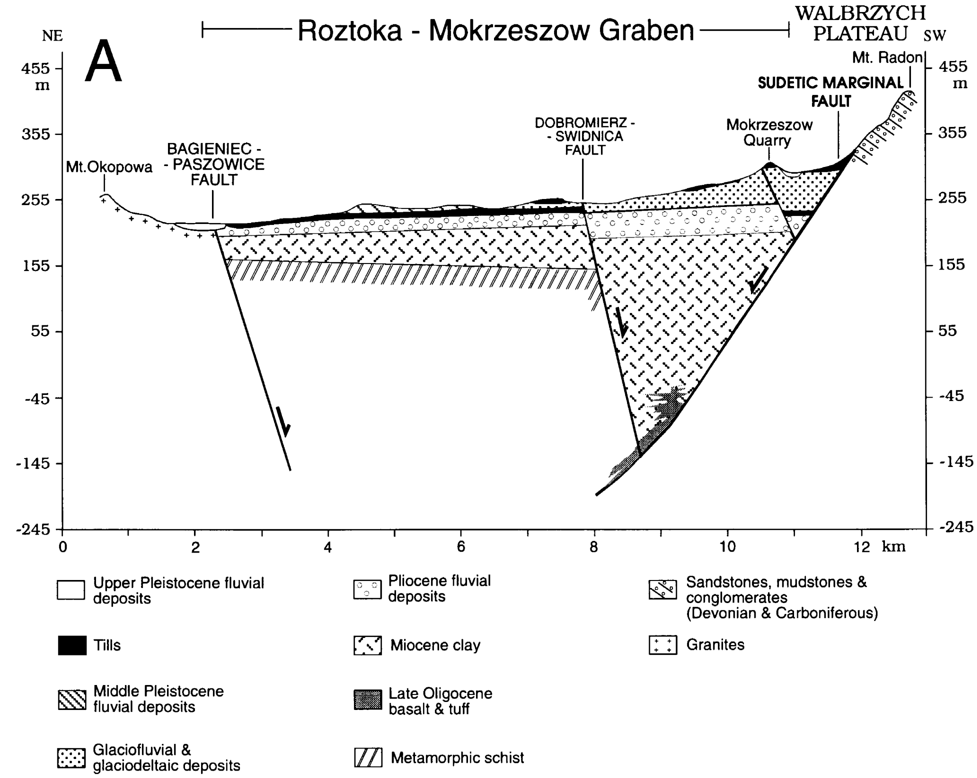
Figure 1. Location map. Shaded areas show the main Late Cainozoic volcanic activity in the Sudetic Foreland

Mountains along the SMF, based on the divergence of river terraces in a downstream direction. Considering the maximum altitude of Scandinavian erratics in the Sudetic Mountains, Schwarzbach (1942) suggested differential Quaternary uplift, with maxima in the Sowie Mountains. Mastalerz and Wojewoda (1990) interpreted intraformational load structures in Lower Pleistocene deposits on the SMF as seismically triggered deformations. Lately, Krzyszkowski (1990, 1991), Krzyszkowski and Pijet (1993) and Krzyszkowski and Migon (1995) have demonstrated possible Pleistocene tectonic activity shown by down-faulted terraces and alluvial fans along the SMF. They also indicated tilting and downstream divergence of terraces in the mountain valleys and knickpoints on the SMF in longitudinal profiles of rivers. Historical earthquakes, although rare, have also been recorded along the SMF (Pagaczewski, 1972; Prochazkova *et al.*, 1978; Ciezkowski and Koszela, 1988).

In this paper we focus on new evidence, including distinct sediment deformations and morphotectonic features, which may suggest neotectonic activity along the SMF zone.

STUDY AREA AND STRATIGRAPHIC BACKGROUND

The exposures investigated are located in quarries, within 1–2 km of the Sudetic Mountains, in the central section of the SMF. The sites are within the Roztoka–Mokrzeszow Graben, near the city of Swidnica by the Bystrzyca River (Figure 1). The thickness of the graben fill is 250–475 m, including 200–400 m of Miocene and Pliocene deposits, capped with 40–50 m of Quaternary sediments (Figure 2). The thickness of Quaternary deposits beyond the graben is only 10–25 m.



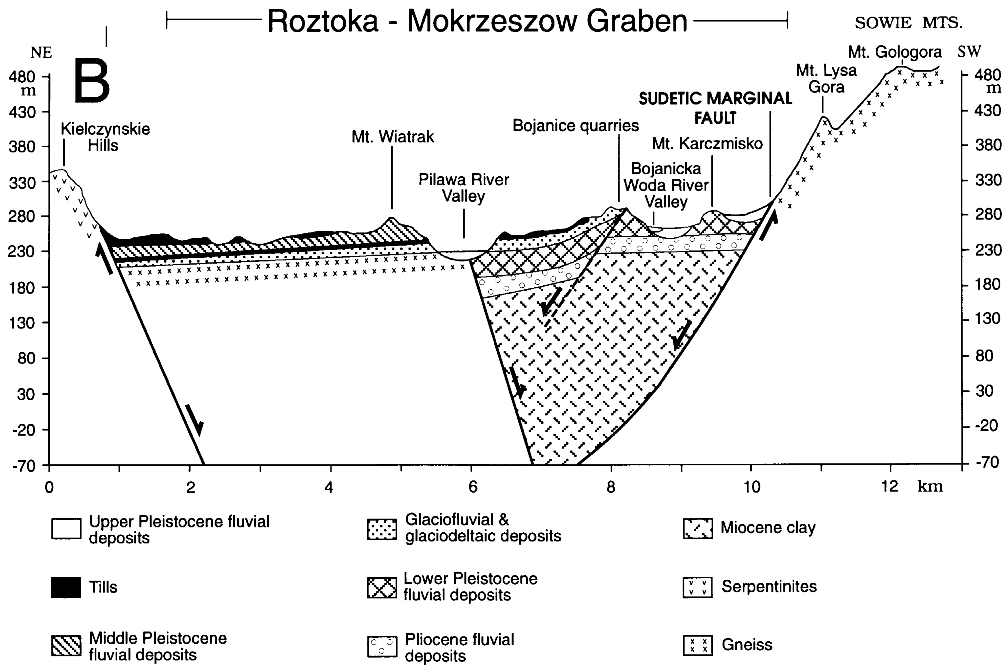


Figure 2. Morphology and general geology at the front of the Sudetic Marginal Fault following in part Dyjor and Kuszell (1977). (A) Section through the Mokrzeszow quarry; (B) section through the Bojanice quarries

The Quaternary deposits in the study area range in age from Lower Pleistocene to Holocene. However, dating is not precise owing to sparse palaeontological and palaeobotanical data. The latter are limited to the Upper Pleistocene, i.e. to Eemian and Weichselian deposits (Dyjor and Kuszell, 1977; Mamakowa, 1989; Krzyszkowski and Blaszczyk, 1994) and to the Holocene deposits (Dumanowski *et al*., 1962). The Lower and Middle Pleistocene stratigraphy of the study area is based only on superposition of deposits, supplemented by petrographic data. The Lower Pleistocene deposits, known also as the 'pre-glacial series', lie directly on Miocene and/or Pliocene sequences and do not contain northern, glacial erratics. These deposits contain only local fluvial material: milk quartz, Sudetic porphyres, Sowie Mountain gneiss, quartzites and Palaeozoic siliceous rocks. Besides the local rocks, the Middle Pleistocene deposits also contain small fluvial deposits or large glacial admixtures of Scandinavian material: red granitoides, Silurian–Devonian 'Baltic' limestones and Jotnian sandstones as well as Mesozoic limestone, sandstone and flint from either the southern Baltic area or the Polish lowland. The area close to the SMF was occupied three times by the Scandinavian ice-sheets (Badura *et al*., 1992). The lower tills have been interpreted as representing the Elsterian glaciation. The uppermost exposed till represents, by definition, the Lower Saalian age, the last glaciation phase to reach the Sudetic Mountains (Schwarzbach, 1942; Jahn and Szczepankiewicz, 1967).

The greatly inclined, flat to hilly area in front of the SMF is composed of Lower and Middle Pleistocene alluvial fans, alternating with Elsterian and Lower Saalian glacial deposits. The morphology is of a plateau-like piedmont (Figure 2), which in post-glacial times (post-Lower Saalian) became entrenched to an average depth of 15–25 m, with three terraces (Figure 2) which represent most probably the Upper Saalian/Eemian, the Middle Weichselian and the Holocene (Krzyszkowski and Migon, 1995).

PROCEDURES

An initial survey of all outcrops within the Sudetic foreland in front of the SMF was undertaken, including all quarries in the Roztoka–Mokrzeszow Graben. Three quarry exposures with clear indications of sedimentary deformation became the focus of this study: Bojanice quarries 1 and 2 and the Mokrzeszow quarry (numbered 1, 2 and 3, respectively, in Figure 1). The initially smaller Mokrzeszow quarry has been described by Cramer *et al*. (1924b), Szczepankiewicz (1961) and Jahn (1981). These authors suggested a glaciotectonic trigger for the deformations. The Bojanice quarries have not been studied before. Maximum wall height was about 10 m in quarry 1, 20 m in quarry 2 and 25 m in quarry 3. The length of all quarry walls was 50–200 m, thus providing a substantial exposure area.

Field examination included mapping and systematic description of the outcrops, including the stratigraphy, the textural and lithofacial characteristics, major unconformities, the soft-sedimentary deformation structures and faults. The directions of palaeochannels, based on gravel imbrication and cross-bedding, were also recorded. All outcrops were systematically photographed.

Random gravel samples of a few kilograms were taken and the pebbles, in the range 10–35 mm, were petrographically defined for differentiating the Scandinavian glacial source from the local, fluvial pre-glacial deposits. Gravel petrography was supplemented by heavy mineral analysis of the 0·1–0·25 mm fraction. In order to recognize possible morphological traces of neotectonic activity, the drainage patterns were examined. Topographic (1:25 000) and geologic maps were used (Finckh, 1919; Dathe and Finckh, 1924; Cramer *et al*., 1924a).

DESCRIPTION OF THE SEDIMENTS AND THE DEFORMATIONS

Bojanice quarry 1

Stratigraphy. Bojanice quarry 1 comprises three stratigraphic units: the pre-glacial series (Lower Pleistocene), the glaciofluvial series (Middle Pleistocene, Elsterian or Lower Saalian) and the diamicton layer between the two (Figure 3). The definition of pre-glacial deposits is based on the absence of any Scandinavian component (Table I), thus indicating only local provenance. In contrast, the glaciofluvial deposits contain large amounts of northern rocks, as well as amphibole, the main glacial mineral (Tables I and II). The precise age of the glaciofluvial deposits is unknown as they are not found within any glacial sequence.

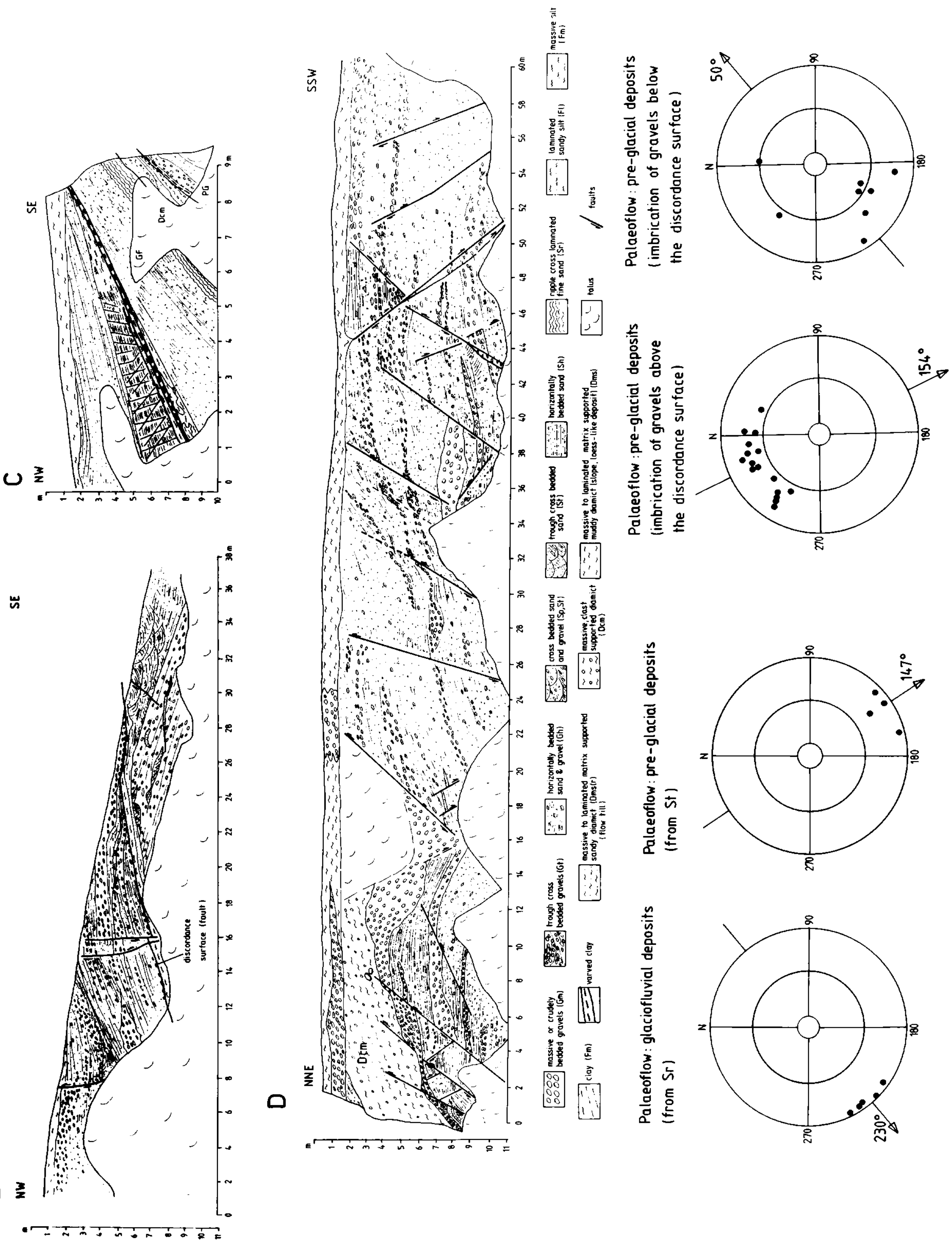


Figure 3. Selected sections at Bojanice quarry 1. Section E: a gently inclined fault with reorientation of strata and with imbrication below. Section C: the contact between the glaciofluvial deposits (GF) and the pre-glacial deposits (PG) with the diamicton layer in between (Dcm). Note the steeply inclined deposits (35–60°). Section D: subhorizontal pre-glacial deposits. Note the conjugate pairs of subvertical faults. On the left is the diamicton layer (Dcm). The strata are inclined only 10–20°. Bottom: palaeoflow measurements from deposits of Bojanice quarry 1. Small circles on Schmidt stereonet indicate 40° and 80°, respectively.

Table I. Lithological composition (per cent) at Bojanice and Mokrzeszow quarries.

	Local rocks					Glacial rocks				
	Milk quartz	Sowie Mtns gneiss	Sudetic porphyre	Quartzite	Siliceous rocks	Red granitoides	Baltic limestone	Jotnian sandstones	Mesozoic limestones/ sandstone	Flint
Bojanice 1 (Pre-glacial deposits)	34–42	4–9	36–46	7–12	2–4	–	–	–	–/–	–
Bojanice 1 (diamicton between pre-glacial and glaciofluvial deposits)	4	7–8	30	7	7	–	–	–	–/–	–
Bojanice 1 (glaciofluvial deposits)	7	17	–	9	4	17	23	1	3/–	–
Bojanice 2 (pre-glacial deposits)	35–44	2–7	38–39	5–8	3–6	–	–	–	–	–
Mokrzeszow 3 (glaciofluvial deposits)	3–4	–	1	3–6	1	32–36	35–45	2–3	3–8/3–5	1

Table II. Mineralogical composition (per cent) at Bojanice and Mokrzeszow quarries.

	Local minerals						Glacial rocks		
	Garnet	Zircon	Cyanite	Syllimanite	Tormaline	Biotite	Amphibole	Epidote	Pyroxene
Bojanice 1 (Pre-glacial deposits)	3–29	6–44	1–4	2–45	1–3	16–88	0–30	0–1	0–6
Bojanice 1 (diamicton between pre-glacial and glaciofluvial deposits)	13	37	10	7	6	–	16	3	3
Bojanice 1 (glaciofluvial deposits)	9–25	8–15	6–15	–	2–7	0–1	27–42	2–8	9–13
Bojanice 2 (pre-glacial deposits)	21	24	9	10	3	11	4	3	3
Mokrzeszow 3 (glaciofluvial deposits)	32–79	0–5	0–4	–	0–6	0–20	17–46	2–6	1–5

Two lithofacies predominate within the pre-glacial series (Figure 3): horizontally bedded sand and gravel (Gh), and massive to crudely bedded gravel (Gm). The latter are clast-supported and of open framework type. Closed framework gravels also occur, with small pebbles and sand as matrix. These two main facies are accompanied in places by trough cross-bedded sands or by sand and gravel (St, Gt), horizontally bedded sand (Sh) and only sporadically by rippled fine sands (Sr) and massive silt (Fm). The pre-glacial deposits probably represent a braided river depositional environment. Their petrological features indicate that they represent the alluvial fan of the Bystrzyca River with its apex located 3 km to the west (Figure 1). Palaeoflow directions, measured from cross-bedding and gravel imbrication, are from the NW and the SW (Figure 3).

The glaciofluvial series are composed of sands, sands and granules, silt, varved clay and one layer of laminated, matrix-supported sandy diamict within coarser deposits. All sediments are uncemented and loose. The sandy sediments are usually horizontally bedded (Sh), with some rippled sand beds (Sr). The silts are laminated (Fl) and occur together with varved clay and rippled fine sands. The glaciofluvial series represents a wide range of depositional environments, from braided river conditions through glaciodeltaic fine sands and silts to glaciolacustrine varved clays. The palaeoflow direction is from the NE (Figure 3).

A 0·5–1·0 m thick diamicton layer was observed at the boundary between the pre-glacial and glaciofluvial series (Figure 3). This is a massive, clast-supported deposit (Dcm), with some sandy-silty matrix between the clasts. The gravel is the same size as in the pre-glacial series and indicates the petrography of the local rocks (Table I), although the heavy minerals indicate rather a mixture of local and glacial material (Table II). The local provenance of the gravel completely excludes a glacial origin for the diamicton layer. From a petrological point of view it represents a mixture of coarse-grained pre-glacial and fine-grained glaciofluvial deposits.

Figure 4. Subvertical (50–80°) glaciofluvial deposits of Bojanice quarry 1 interpreted as part of a flexural zone. Rod at lower right is 1m long. NE is on the right

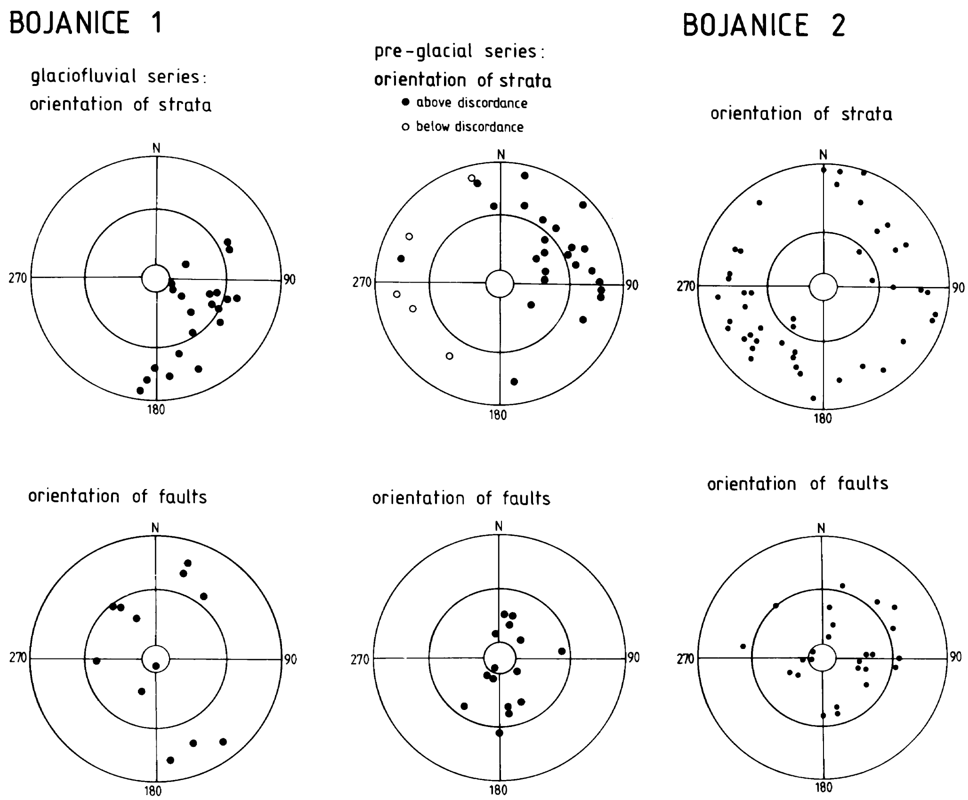


Figure 5. Structural measurements at Bojanice quarries: note the dissimilar orientations of the glaciofluvial and pre-glacial deposits above the discordance at Bojanice 1 and the reorientation of the strata below it. Variable orientations of strata are shown at Bojanice 2. The orientation of the subvertical faults shows a girdle pattern in both quarries and in all types of deposits. Small circles on Schmidt stereonet indicate 40° and 80°, respectively

Deformation structures. The glaciofluvial deposits, which are in a subvertical position (>80°) near the boundary with the pre-glacial series, gradually become less deformed in the NE direction (Figure 3 and 4). This layer and the neighbouring pre-glacial deposits are also steeply inclined, but the dips become 15–25° within a few metres (Figure 3). In the southern part of the quarry (Figure 3, section E) there is a discordance within the pre-glacial series. The strata below and above this surface (Figure 5) show different orientations as well as different directions of gravel (Figure 3). A distinct progressive reduction in the thickness of the sandy beds is

visible down the surface (Figure 3, section E). These facts, and the planar character of the discordance, may suggest that it represents a gently inclined fault plane.

Subvertical faults dipping 40–88° are superimposed on all deformed sediments. Grabens are often observed (Figure 6) formed by conjugate pairs (Suppe, 1985), indicating extension. On the stereonet the directions of the faults in the pre-glacial and glaciofluvial series show a girdle pattern (Figure 5).

Bojanice quarry 2

Stratigraphy. Bojanice quarry 2 is located about 200 m south of quarry 1. It comprises only pre-glacial deposits, with the same petrological characteristics as quarry 1 (Tables I and II) but with more gravel (Figure 7). The sediments are uncemented to loosely compacted. The main lithofacies are massive or crudely bedded gravel (Gm) and trough cross-bedded gravel (Gt), including wedge-shaped mega-channels, 7–15 m wide in an oblique cross-section. Other common facies are horizontally bedded gravel and sands (Gh, Sh), trough cross-bedded sands (St), ripple fine sands (Sr) and massive silts (Fm). The fine-grained facies occur only in the lower part of the quarry and are interbedded with horizontal coarse sands and gravel. Large troughs and massive gravel dominate the upper part of the section.

The pre-glacial sequence of quarry 2 represents a braided river environment, similar to that of quarry 1. However, it reflects an increase in stream power, marked by coarsening upward and erosional channels. Palaeoflow measurements on troughs and on gravel imbrication do not indicate any consistent flow direction, and often show unexpected directions with respect to the fan morphology, e.g. from E and NE (Figure 7).

Deformation structures. The deposits in quarry 2 are steeply inclined (20–60°), especially in the lower part of the sequence (Figure 7). The flexed deposits often return sharply, within a few decimetres, to a subhorizontal position. The ‘discordance’ between the subvertical and subhorizontal beds indicates, most probably, a fault contact between blocks (Figure 7). The inconsistent palaeoflow directions may thus be explained by the different tilting of the blocks.

Figure 6. A graben formed by conjugate subvertical faults at Bojanice quarry 1

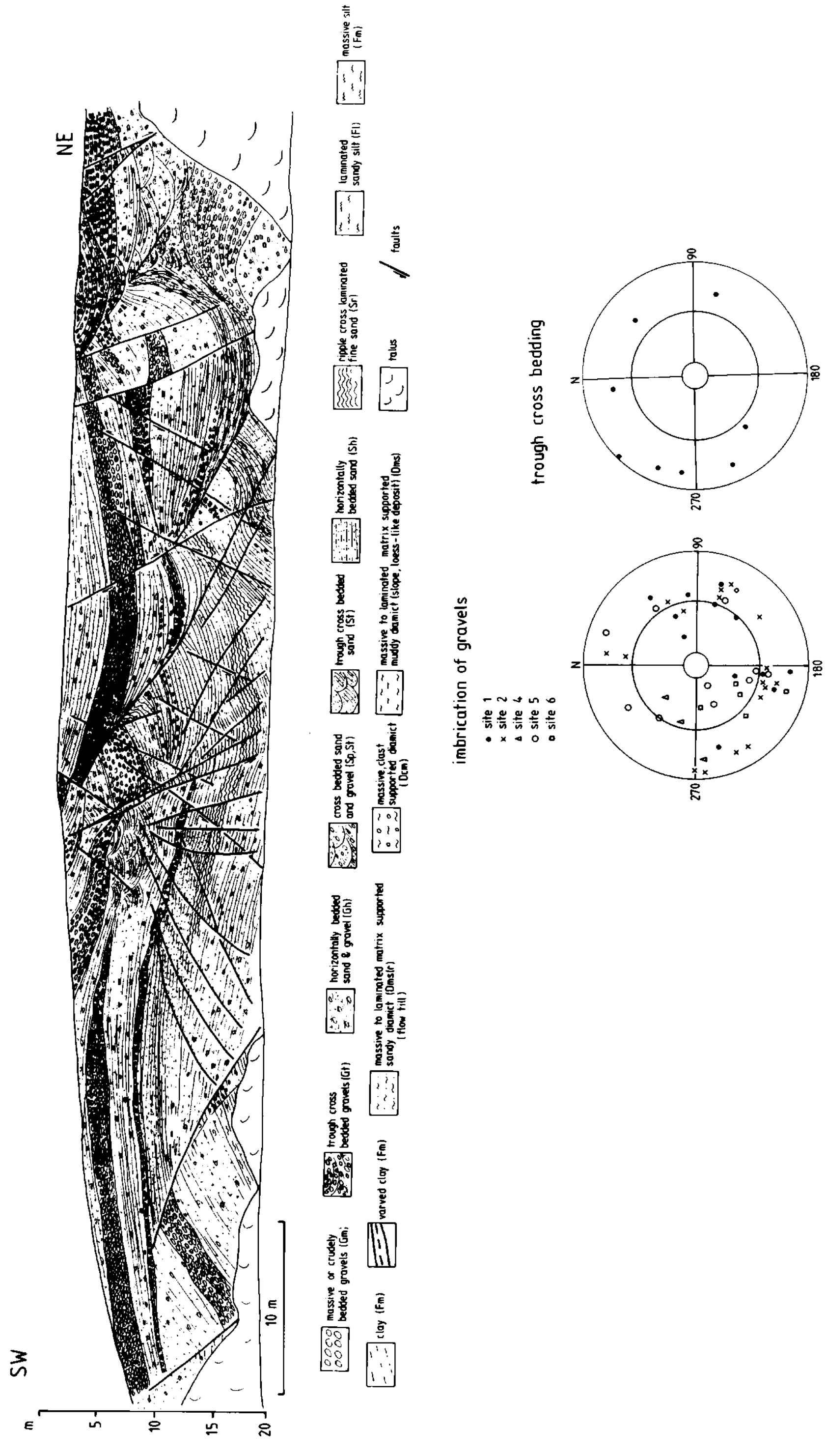


Figure 7. Bojanice quarry 2, showing a complex fault pattern including gently inclined faults, subvertical faults with reorientation of strata from subhorizontal to subvertical positions and a set of faults with small (not to scale) displacements. Bottom: Palaeoflow measurements of deposits in Bojanice quarry 2. Note lack of preferred orientation. Small circles at Schmidt stereonet indicate 40° and 80°, respectively

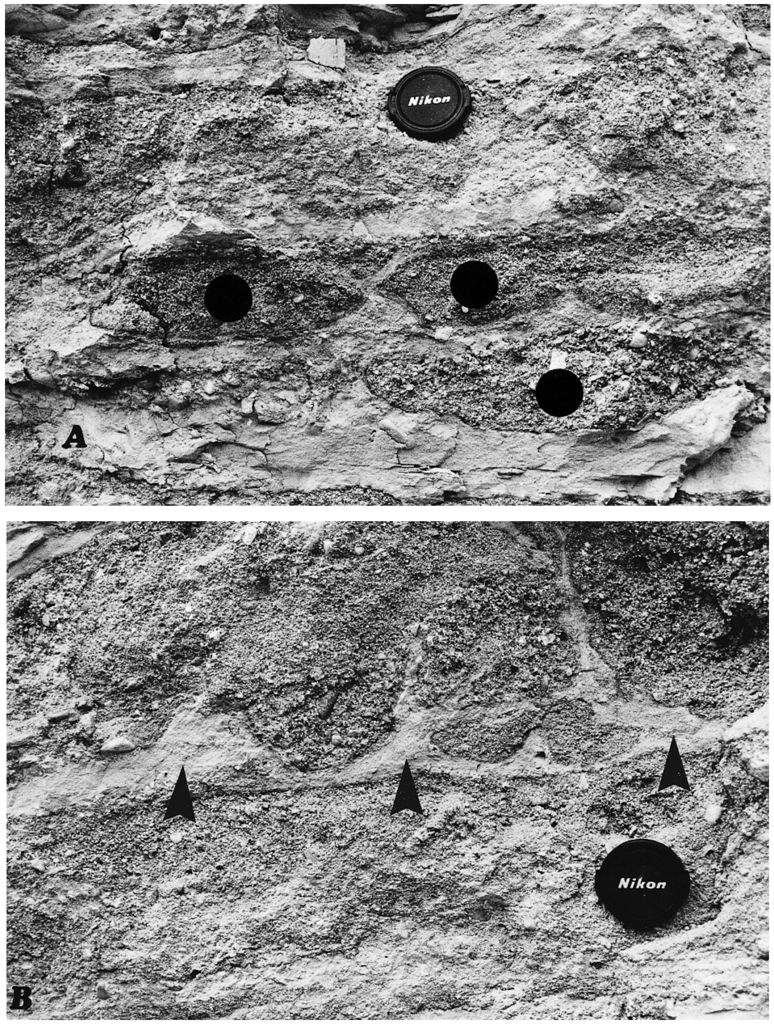


Figure 8. Soft-sediment deformation structures at Bojanice quarry 2. (A) ‘Pseudonodules;’ or ‘isolated balls’ (black circles). (B) flame structures (arrows)

Faults with normal offsets of a few centimetres up to 0·5 m are common, dipping 20–82° in variable orientations (Figures 5 and 7). The fault planes are often curved, sometimes with a distinct trend of steepening down the sequence (Figure 7). Some reversed, subvertical faults have also been observed with displacements from several centimetres to 0·5 m. Massive silts in the lower part of the sequence show soft-sediment deformation structures, including clusters of sand nodules, downward-sagging bulges of load casts and flame structures (Figure 8).

Mokrzeszow quarry

Stratigraphy. The Mokrzeszow quarry (Figure 9) comprises only glacial deposits (Tables I and II): 25 m thick gravelly sediments topped with 1–3 m thick till. Several boring profiles near Mokrzeszow have indicated another till horizon below the gravel. The age of the till observed in the quarry was proposed by Dyjor and Kuszell (1977) and by Jahn (1981) to be Lower Saalian, taking into account its position at the ground surface and above the older till.

The glacial deposits of the Mokrzeszow quarry vary in grain size from silt to boulder grade. They consist of foresets, 2–8 m high, with large-scale planar cross-bedded gravel (Gp facies) and massive to reverse-graded boulders and cobbles with coarse sand and granule as matrix (Gms). Sandy facies are represented by planar and trough cross-bedded sands (Sp, St), horizontally bedded sands (Sh), ripple fine sands or sandy silts (Sr). These

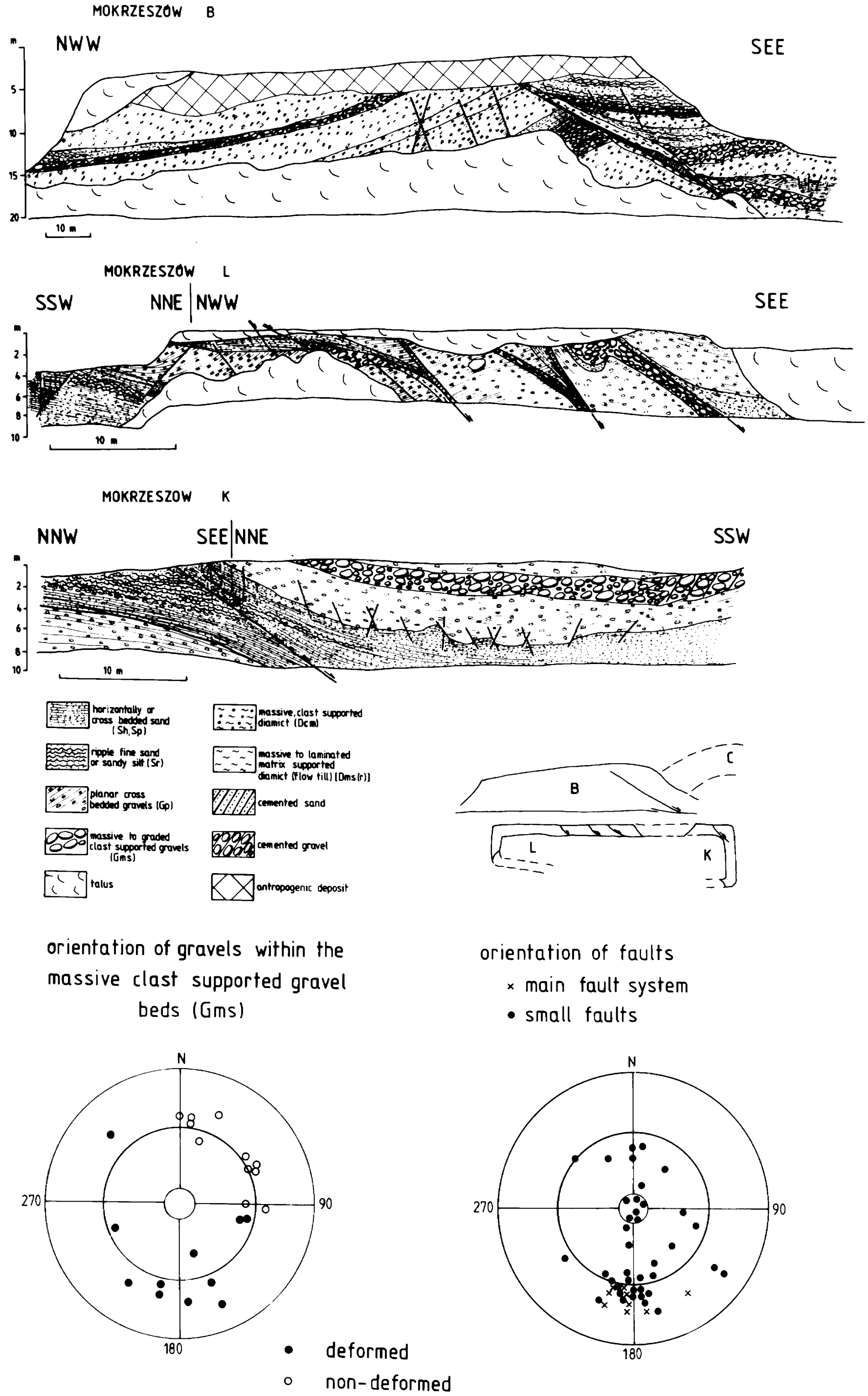


Figure 9. Selected sections in Mokrzeszow quarry. Section B: a gently inclined ‘main’ fault (right) separating the subhorizontal strata from the deformed deposits along the fault plane. Note the different number of sedimentary cycles on either side of the fault and the occurrence of diamicton layers (Dcm). Section L: small, gently inclined faults (compare with Figure 10A). Note transition to a flexure at the top of some faults. Section K: boudinage along the ‘main’ fault (compare with Figure 10B) in the centre of the section, directly above the fault plane (arrow). In all sections cementation is post-depositional. Bottom: Palaeoflow measurements based on imbrication of gravel. Note the reorientation of the deformed gravel, the orientation of the main fault system and the girdle pattern of the small faults. Small circles on Schmidt stereonet indicate 40° and 80°, respectively

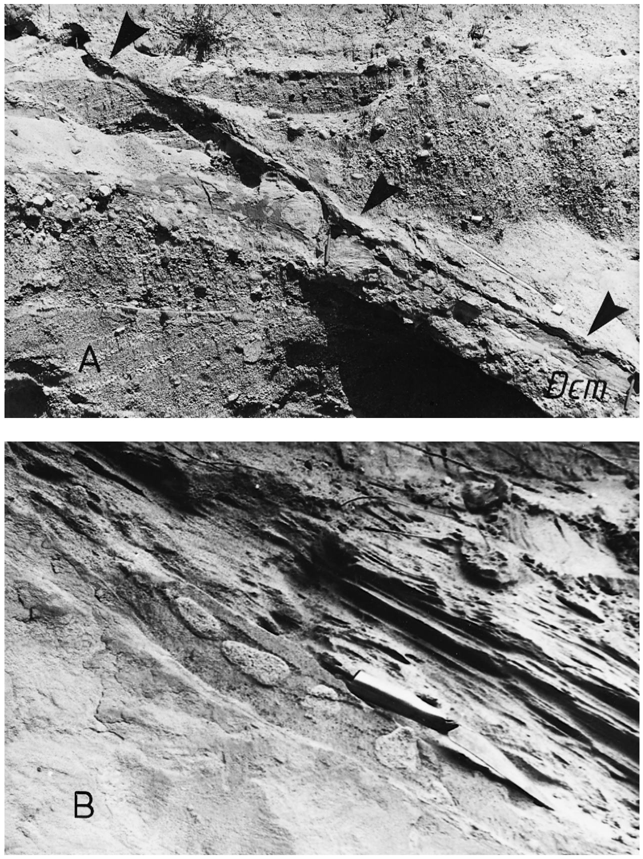


Figure 10. (A) The gently inclined fault at Mokrzeszow quarry (compare with Figure 9, section K). The fault plane is indicated by arrows. Note the occurrence of diamicton (Dcm facies) along the fault and the reorientation of strata near the fault plane. Rod at the right is 1 m long. SE is to the right. (B) Boudinage along the 'main' fault (for location see Figure 9, section L). The sandy nodules are separated owing to post-depositional differential cementation. The shovel is 30 cm long. SE is to the right

three facies groups – gravelly foresets, massive gravel and the sandy facies – form at least six sedimentary cycles which represent a prograding Gilbert-type delta (Figure 9). The closeness to the ice-sheet is confirmed by the occurrence of thin layers of flow till in the form of massive to laminated muddy, matrix-supported diamictons in the coarse deposits (Dms facies).

The second type of diamicton was observed only along the fault planes (Figure 9 and 10A). It is a clast-supported, massive diamiction with some silty-sandy matrix (Dcm facies). Its thickness varies from a few centimetres to 0·5 m, and it is often cemented. The closeness of the Dcm facies to fault planes and its structure may indicate a tectonic breccia.

Deformation structures. The glaciodeltaic sediments of the Mokrzeszow quarry are mainly subhorizontal, and only in some places are they faulted. Two fault systems have been observed. The 'main' fault system runs W–E, oblique to the SMF. It consists of a zone of many small parallel faults which die out after a short distance. One of these (Figure 9, section B) is a gently dipping fault (15–30°) which crosses the entire sequence, while offsetting the sediments by about 20–30 m and reorienting the gravel (Figure 9). Clast-supported diamicton beds (Dcm facies), 30–60 cm thick, occur along the fault zone indicating a tectonic breccia. Some additional faults, also dipping gently but crossing only a part of the sequence, are associated with this system (Figure 9, section K). They occur only in the upthrown block. In the downthrown block the sediments are tilted along the fault plane (Figure 9), with occasional boudinage structures (Figure 10B). The 'small' fault system is represented by numerous subvertical normal faults, often forming conjugate pairs, with displacements of a few centimetres up to 0·5 m (Figure 9). This fault system is exposed within the entire sequence and terminates vertically below the ground surface.

INTERPRETATION OF THE DEFORMATION STRUCTURES

The 'main' fault in the Mokrzeszow quarry bears characteristics of a normal fault formed in an extensional regime. The following features, besides the offset of the sequence, confirm this interpretation: (1) the fault does not form a single plane but a zone of serial faults; (2) the fault zone is gently inclined; (3) sediments are dragged along the fault, with fabric reorientation; (4) tectonic breccia (Dcm diamicton) is formed along the fault zone; (5) boudinage structures occur within the fault zone; (6) the main fault is associated with additional, much smaller faults with similar characteristics, which clearly developed from flexural deflection of the deposits (Figure 9, section K, and Figure 10A).

Bojanice quarry 1 contains some deposits and deformations which are similar to those of Mokrzeszow. These include gently inclined faults with reorientation of strata (Figure 3, section E) and the diamicton (Figure 3, sections C and D), which may be interpreted as a tectonic breccia. The diamicton occurs in a section of vertical deposits, attributed to the strong tectonic deformation in the flexure zone (Figures 3 and 4).

Bojanice quarry 2 probably contains several blocks which are differentially tilted. The occurrence of gently dipping faults together with subvertical reversed faults may, however, suggest a flexural zone. The tendency of the faults to become steeper down the sequence may suggest vertical movements but may also be explained by change in texture, which becomes finer towards the lower part of the section.

The data from all quarries suggest that the deformed sediments, especially the vertical deposits at Bojanice 1 and the 'main' fault zone at Mokrzeszow, represent flexural zones. The flexured sediments may also be composed of several tilted blocks, separated by flat faults, as observed at Bojanice 2 (Figure 7). According to this model, the cause of flexing and faulting may be the tectonic extension of the Roztoka–Mokrzeszow Graben (Figure 11). The 'main' fault at Mokrzeszow quarry is oblique to the SMF and forms an antithetic deformation zone (Figure 2A). Bojanice quarries 1 and 2 are probably located along the other oblique fault zone, although homothetic in relation to the SMF (Figure 2B).

Former authors interpreted the deformation at Mokrzeszow as glaciotectonic structures (Cramer *et al*., 1924b; Szczepankiewicz, 1961; Jahn, 1981). Glaciotectonic structures usually form due to compressive pressures (Aber *et al*., 1989) and are represented by thrust structures, inclined, recumbent or overturned folds and, more rarely, by diapir-like structures. The glaciotectonic structures occur in series, with cyclic stratigraphic sequences. Faults of all types may also occur (Aber *et al*., 1989). However, none of these structures has been observed in the quarries described. Thus it seems that the observed deformations are better explained by the tectonic trigger, rather than glaciotectonism. This, however, cannot be concluded with certainty as glaciotectonic zones may locally also contain structures of extension (Aber *et al*., 1989; van der Wateren, 1987).

The soft-sediment deformations in Bojanice 2 (Figure 8) may be seismic structures, if located near a potential seismic focus and if a substantial lateral extent and a regional occurrence can be shown (Allen, 1986). Along with the deformed structures observed by Mastalerz and Wojewoda (1990) in the pre-glacial deposits of the northern sector of the SMF, the seismic indication seems more convincing.

All three quarries show small, normal subvertical faults with usually small displacements and different orientations. These faults are superimposed on older features, i.e. on the flexures and on the 'main faults', and displace them. The dominant normal faulting mode and the fault orientations suggest an extensional stress regime. The subvertical faults represent a quite different and younger deformational episode. Its origin is, however, quite ambiguous as small-scale normal faulting may be formed in several ways, e.g. unloading on slopes, compaction, etc.

DISCUSSION

The field data enable the resolution of two sets of deformational episodes which differ in origin and magnitude. The 'main' system includes gently inclined faults and/or flexures with displacements up to 25 m. The 'secondary' deformational system, which is superimposed on the former one, includes normal faults with small displacements, never exceeding 0·5 m. Both systems have an extensional nature. If the magnitude of deformation reflects the power of the event (Sie, 1978), then the 'main' fault system indicates the larger event.

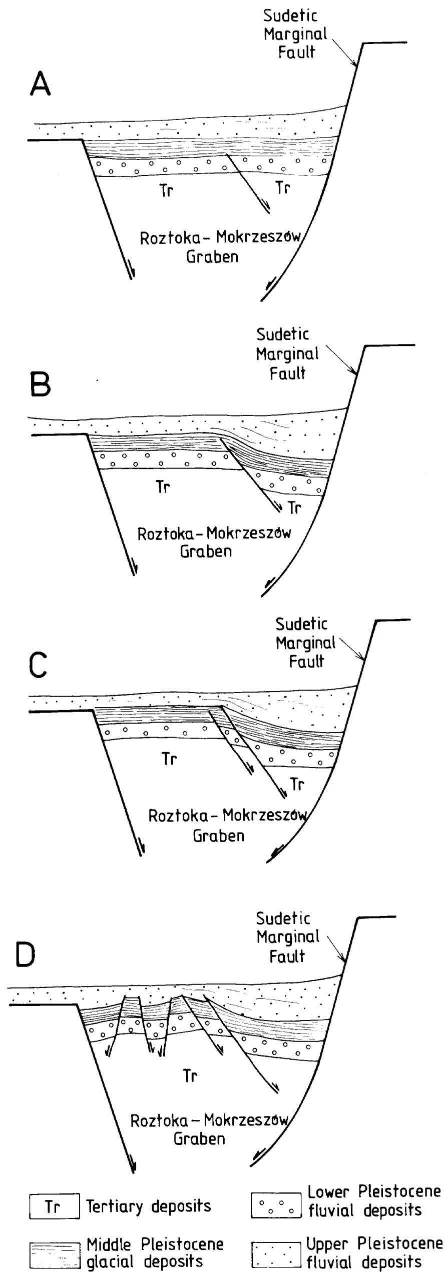


Figure 11. A model depicting the development of the 'main' deformational system in the quarries at Bojanice and Mokrzeszow: (A) The initial stage of formation of the gently inclined fault due to subsidence. (B) Formation of a flexure along the fault: this stage is documented in Bojanice quarry 1 by the steeply inclined sands, the diamicton, the gravel (compare with Figure 3, section C, and Figure 4) and the 'discordance surface' (Figure 3, section E). (C) As subsidence continues the flexural zone is further broken down and secondary faults are formed on the up-thrown limb. This situation corresponds to data from Mokrzeszow quarry (Figure 9). (D) Intensive down-faulting and differential tilting of the 'blocks'. This is the final stage of deformation documented in Bojanice quarry 2 (Figure 7)

A tectonic origin is suggested for the deformations of the ‘main’ system (Figure 11). The structural data do not contradict such an interpretation. However, as the observations have been collected only in shallow quarries, they do not confirm it with certainty. No direct observation is available to prove the relation between the ‘main’ fault/flexure system in the quarries and the bedrock faults. However, there is more indirect evidence which may corroborate our interpretation: the extensional nature of the surficial deformations at the front of the Sudetic Marginal Fault, along a distance of about 20 km from Mokrzeszow to Bojanice, corresponds well with the general extensional tectonics of the region during the late Cainozoic. Moreover, the Mokrzeszow quarry is located within that part of the Roztoka–Mokrzeszow Graben which showed the largest subsidence during Neogene and Pleistocene times, with a maximum thickness of deposits of *c.* 400 m (Dyjor and Kuszell, 1977). This zone migh have been susceptible to tectonic deformations.

The structural data from the Bojanice quarries can be supported by morphological and geological data. The fault line suggested by Zelazniewicz (1987) in the Sowie Mountains gneiss (Figure 12, line C–D), based on displacements of veins and on orientations of joints, and the fault line delimiting the gneiss and granite outcrops in the foreland, suggested by Dyjor and Kuszell (1977, Figure 12, line E–F), based on the maps of Dathe and Finckh (1924) and Finckh (1919, 1923), together make a single, somewhat curved trace line crossing the Bojanice quarries. Thus, the investigated quarries occur most probably above this fault line in the bedrock.

The well developed meander belt along a 4 km segment of the river, just before joining the Bojanicka Woda trunk (Figure 12, indicated in bold), forms a local sinous belt in between relatively straighter reaches of the river. Following the experiments of Ouchi (1983) and Schumm (1986), such features comprise the typical fluviomorphological response to recent uplift. Other rivers along the SMF show a similar fluvial pattern (Zeuner, 1928; Krzyszkowski and Migon, 1995), which may suggest an extended uplifted zone.

There are, however, other indications of tectonic control. Figure 12 demonstrates the rectangular pattern of both the Bojanicka Woda and the Ceglany Potok rivers. Both are deflected from the regional SW–NE flow direction towards the linear front of the Bojanickie Hills, a 40 m high relief, with Bojanice quarries 1 and 2 on its top. The linear front of the Bojanickie Hills is interpreted as a fault trace which dies out gradually southeastwards. The Mala Lutomka River course (Figure 12, dashed line) indicates this decay by passing undeflected and following the initial topography in the SW–NE direction. Many similar deflections were documented along the front of the Sowie Mountains by Migon (1994) and were interpreted as indications of neotectonic rejuvenation. Thus, the morphology near Bojanice could indicate faulting oblique to the SMF (Figure 12).

The glaciotectonic interpretation, if introduced, would assume extraordinary extensional subglacial conditions. Also, it would assume glaciotectonic push from the southeast, following the data from Mokrzeszow, or from the east following data from Bojanice. Both directions are inconsistent with the regional glacial advance, which was, based on till fabrics and gravel petrography, from the northwest, north or northeast (Jahn, 1981; Badura *et al.*, 1992; Krzyszkowski and Czech, 1995).

Hence, we prefer one tectonic episode of oblique flexuring and faulting along the Sudetic Marginal Fault as an explanation for the ‘main’ deformations at Mokrzeszow and Bojanice. The unsolved problem which still remains is the source of the extensional stress, which caused gently inclined faults and flexures. Such structures are usually formed under large hydrostatic pressure. The observed structures have been found in a subsurface position, and were most probably never overlain by a sequence thicker than several metres. However, the large extensional stress in the active graben may have occurred due to strong loading by the advancing Scandinavian ice-sheet approaching the Sudetes Mountains (Schwarzbach, 1942; Jahn, 1981). This could have reactivated both the Sudetic Marginal Fault as well as the grabens at its foreland.

The age of the deformation is assumed to be Lower Saalian, based on the youngest deformed glaciodeltaic deposits at Mokrzeszow, which are conventionally related to the Lower Saalian. The glaciofluvial deposits of Bojanice 1 may also be of Lower Saalian age. Lower Saalian activity on the SMF was concluded earlier from morphological data and from terrace superposition by Krzyszkowski (1991), Krzyszkowski and Pijet (1993) and Krzyszkowski and Migon (1995). It is consistent with the age of sediment deformation in the Roztoka–Mokrzeszow Graben. Lower Saalian tectonic activity was also documented in central Poland (Krzyszkowski, 1989, 1992). This may suggest a more regional tectonic activity at that time, although its relation to an ice-sheet advance is ambiguous.

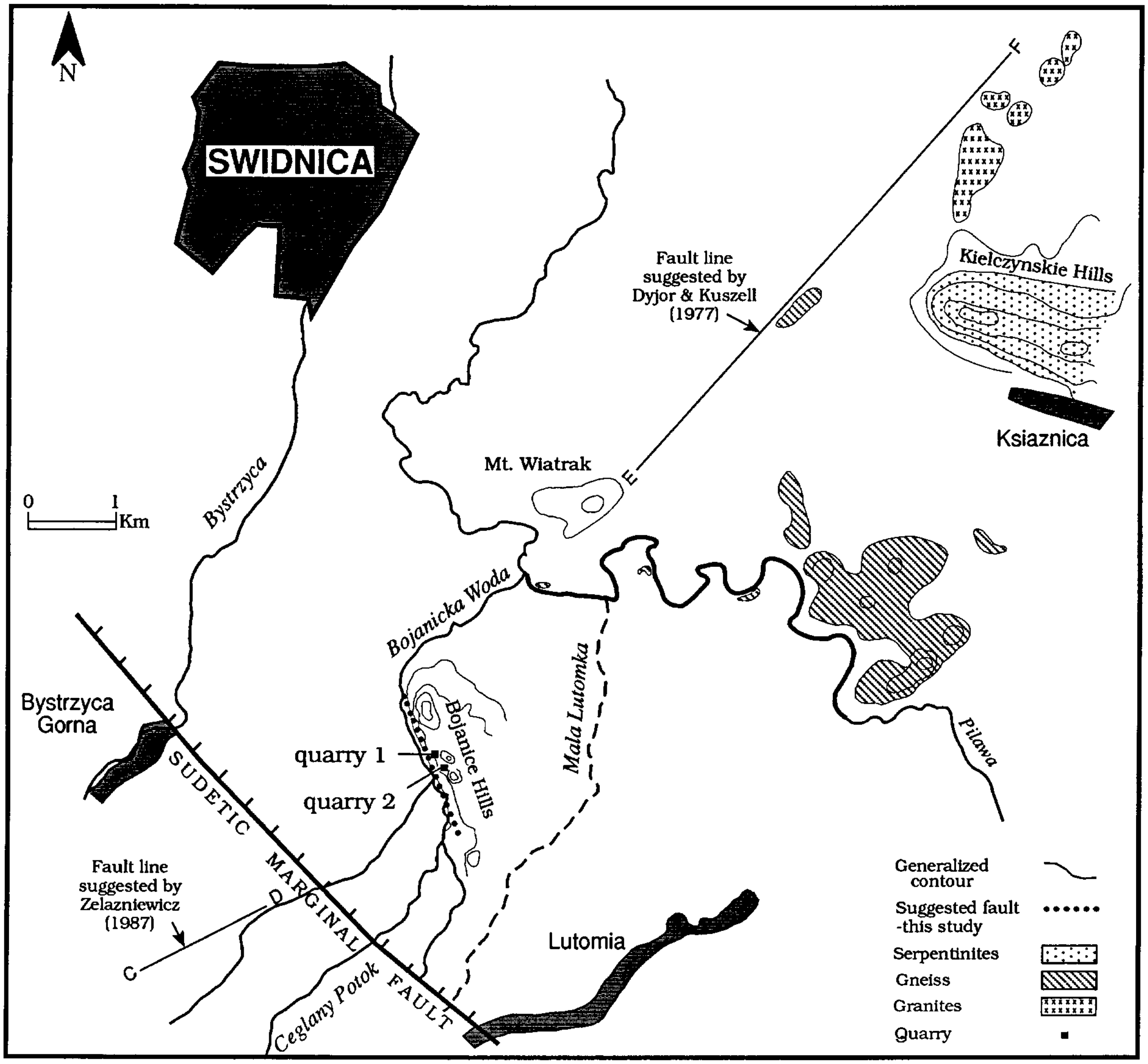


Figure 12. Probable morphological indicators of Quaternary faulting near Bojanice. Note that faults C–D and E–F may form a continuous line. The meanders on the up-thrown block are shown in bold. The rectangular pattern of the rivers near Bojanice may suggest faulting oblique to the Sudetic Marginal Fault

CONCLUSIONS

1. The Quaternary deposits of the Roztoka–Mokrzeszow Graben exhibit two extensional deformation phases. The main deformation was of tectonic origin and connected with movements along the Sudetic Marginal Fault. The younger phase of deformation formed small extensional faults, most probably due to surficial unloading.
2. The Quaternary tectonic deformation in the Roztoka–Mokrzeszow Graben includes mainly normal, gently inclined faults and flexures with displacements of at least several metres. These faults are oriented obliquely to the Sudetic Marginal Fault and most probably follow faults in the bedrock.
3. The age of the tectonic deformation was Lower Saalian (Upper Middle Pleistocene). This age is consistent with the activity of the Sudetic Marginal Fault documented by morphological data, and with the age of some tectonic deformations in central Poland.

4. The data strengthen the conclusions from former morphotectonic studies (Krzyszkowski, 1991; Kryszkowski and Pijet, 1993; Krzyszkowski and Migon, 1995; Migon, 1993, 1994; Pijet, 1991) that the Sudetic Marginal Fault has not been dormant during the Quaternary.

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